RESEARCH ARTICLE

A prospective cohort study on ankle joint stability and ligament injury risk in table tennis players during rapid lateral footwork

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Received: December 16, 2024; **accepted:** March 31, 2025.

Ankle injuries pose a significant concern in professional table tennis with lateral ankle sprains being particularly prevalent. The unique biomechanical demands of rapid lateral movements in confined spaces create substantial stress on players' ankle joints, yet the specific relationship between joint stability and injury risk remains incompletely understood. This study investigated the relationship between ankle joint stability and ligament injury risk in table tennis players during rapid lateral footwork movements, focusing on biomechanical and neuromuscular factors that influenced injury susceptibility. A cohort of 120 competitive table tennis players aged from 18 - 35 years old were involved in the study for 24 months. Comprehensive baseline assessments included anthropometric measurements, biomechanical analysis using a 12-camera motion capture system, neuromuscular control assessment through EMG monitoring, dynamic stability testing, and ligament laxity evaluation. Continuous monitoring of movement patterns and injury surveillance were conducted throughout the study period. Multivariate Cox proportional hazards modeling and mixed-effects analysis were employed to identify risk factors for injury. The results showed that, during the follow-up period, 45 ankle injuries were recorded, yielding an overall incidence rate of 4.5 injuries per 1,000 hours of exposure. Significant risk factors for injury included increased Foot Posture Index (HR = 1.4, 95% CI = 1.1 - 1.8), decreased ankle dorsiflexion range of motion (HR = 1.3, 95% CI = 1.05 - 1.6), and altered joint coordination patterns (HR = 1.6, 95% CI = 1.2 - 2.1). Professional players demonstrated higher injury rates compared to semi-professional players (6.5 *vs*. 3.0 per 1,000 hours, *P* = 0.03), and singles players showed increased risk compared to doubles players (5.8 *vs*. 3.7 per 1,000 hours, *P* = 0.04). Neuromuscular analysis revealed significantly higher co-activation indices in the injured group for both Fibularis Longus and Tibialis Anterior muscles. This study provided evidence that ankle injury risk in table tennis players was influenced by a complex interaction of biomechanical and neuromuscular factors. The findings suggested that injury prevention strategies should address multiple components including movement pattern modification, load management, and targeted neuromuscular training. Future research should focus on developing and validating sport-specific injury prevention programs that account for the unique demands of table tennis.

Keywords: ankle stability; table tennis biomechanics; sports injury prevention; neuromuscular control; ligament injury; lateral movement; athletic performance; injury risk factors.

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Introduction

Table tennis is a sport characterized by rapid, multi-directional movements and explosive footwork, particularly during lateral stepping sequences that are fundamental to competitive play. The demanding nature of these movements places significant stress on players' lower extremities with the ankle joint being especially vulnerable to both acute injuries and chronic instability [1]. Recent epidemiological data suggests that ankle injuries account for approximately 15 - 20% of all injuries in professional table tennis with lateral ankle sprains being the most common presentation [2]. The biomechanical demands of table tennis footwork are unique among racquet sports as players must maintain a low center of gravity while executing rapid lateral movements within confined spaces. These movements frequently involve sudden accelerations, decelerations, and directional changes that generate substantial shear forces across the ankle joint complex [3]. Modern playing styles have evolved to become increasingly dynamic with average movement frequencies during competitive matches reported to exceed 150 lateral steps per minute in elite players [4].

The ankle joint's stability during such intensive lateral movements relies on both passive structures including the lateral ligament complex and active neuromuscular control mechanisms [5]. The anterior talofibular ligament (ATFL) and calcaneofibular ligament (CFL) are particularly stressed during the rapid lateral movements common in table tennis as these structures provide primary restraint against excessive inversion and internal rotation of the ankle [6]. Research in other sports involving lateral movements has demonstrated that fatigue and repeated high-intensity efforts can compromise these stabilizing mechanisms, potentially increasing injury risk [7]. While substantial research exists on ankle injury mechanisms in sports such as basketball and volleyball, the specific demands and injury risks associated with table tennis footwork have received limited attention in the scientific literature [8]. Previous studies have primarily focused on general injury patterns or technical aspects of footwork, rather than examining the specific relationships between movement patterns and ankle joint stability [9]. The few existing biomechanical analyses of table tennis footwork have typically employed cross-sectional designs, limiting our understanding of how repeated exposure to these movement patterns affects ankle joint stability over time [10]. The relationship between ankle joint stability and injury risk in table tennis players is particularly relevant given the sport's growing global participation and the increasing physical demands at both recreational and competitive levels [11]. Recent advances in wearable technology and biomechanical analysis methods enable more sophisticated investigation of joint kinematics and kinetics during actual playing conditions, providing opportunities for more detailed prospective studies [12]. Understanding the factors that contribute to ankle joint stability during table tennis-specific movements is crucial for developing targeted injury prevention strategies and optimizing performance [13]. Furthermore, while general principles of ankle injury prevention have been established in other sports, the unique characteristics of table tennis footwork necessitate sport-specific investigation [14]. The combination of rapid lateral movements confined playing spaces, and the need for precise control presents distinct challenges for maintaining ankle joint stability [15]. Recent research has suggested that traditional approaches to ankle injury prevention may need modification to address the specific demands of table tennis [16].

The purpose of this prospective cohort study was to investigate the relationship between ankle joint stability and ligament injury risk in table tennis players during rapid lateral footwork movements with particular attention to the biomechanical and neuromuscular factors that influenced injury susceptibility. This study had significant implications for the current sport community. The findings would inform the development of evidence-based injury prevention strategies specifically tailored to table tennis players, potentially reducing injury rates, and enhancing athletic longevity. Additionally, the biomechanical insights gained might influence coaching practices, equipment design, and training methodologies across competitive levels, ultimately contributing to both athlete safety and performance optimization in this globally popular sport.

Materials and methods

Study design and participants

This prospective cohort study was conducted over a 24-month period from January 2022 to October 2024. All procedures were approved by the Institutional Review Board of Henan Sport University (Zhengzhou, Henan, China) (Approval No. IRB-2022156). The written informed consents were obtained from all participants prior to enrollment. According to a power analysis based on previous studies of ankle injury incidence in racquet sports, a sample size of 120 participants would provide 80% power to detect a hazard ratio of 1.5 with a significance level of 0.05, accounting for an anticipated dropout rate of 15%. Participants were recruited from the Henan Provincial Table Tennis Team, Zhengzhou Technical College Table Tennis Club, and Wuhan Huaxia Institute of Technology Table Tennis Academy. Of the 150 initially recruited participants, 85 (56.7%) were from professional leagues and 65 (43.3%) were semi-professional players. In the professional group, there were 55 males (64.7%) and 30 females (35.3%), while the semi-professional group comprised 38 males (58.5%) and 27 females (41.5%). The inclusion criteria comprised (1) active participation in professional or semi-professional table tennis competitions, (2) age between 18 and 35 years, (3) minimum of five years competitive playing experience, (4) training frequency of at least 20 hours per week, (5) competed in at least ten tournaments annually, (6) no history of lower extremity surgery within the past two years, (7) no current ankle injury or rehabilitation program participation, while the exclusion criteria included (1) history of chronic ankle instability or recurrent sprains (more than three sprains in the past year), (2) current musculoskeletal injuries affecting lower extremity function, (3) neurological conditions affecting balance or proprioception, (4) use of prophylactic ankle supports or orthotics, (5) inability to complete all testing procedures.

Baseline assessment

Prior to the commencement of the study period, all participants underwent comprehensive baseline assessments conducted by a team of experienced sports medicine professionals and biomechanists. Anthropometric measurements including height, weight, leg length, and foot dimensions were recorded using standardized protocols. Body composition was assessed using dual-energy X-ray absorptiometry (DEXA) (Lunar iDXA, GE Healthcare, Chicago, IL, USA) with particular attention to lower limb muscle mass distribution and bone mineral density. A detailed playing history questionnaire documented training volume, competition level, previous injuries, and preferred playing style. The questionnaire was developed through expert consultation and pilot testing with professional table tennis players. Additional sections captured information about training surface preferences, footwear characteristics, and typical warm-up routines. Foot posture and alignment were evaluated using the Foot Posture Index-6 (FPI-6) described by Redmond *et al*. [17], and ankle range of motion was measured using a G360 digital goniometer (Biometrics Ltd., Newport, UK) following standardized procedures in three planes of motion including dorsiflexion, plantarflexion, inversion, and eversion.

Biomechanical assessment

The biomechanical assessment laboratory was equipped with a Vicon Nexus 2.12 12-camera motion capture system (Oxford Metrics, UK) operating at 250 Hz. The capture volume was calibrated daily using a standardized wand calibration procedure, achieving residual errors of less than 0.5 mm. Two Kistler 9287CA force plates (Winterthur, Switzerland) were embedded in a regulation table tennis court surface, sampling at 1,000 Hz with regular calibration verification using known weights. Reflective markers were placed according to a modified Oxford foot model protocol with additional markers on the lower limb to track segmental movements. The marker set included 16 markers per foot and ankle complex with cluster markers on the shank and thigh segments. A static calibration trial was recorded for each participant in the anatomical position followed by functional joint center determination trials for the ankle and knee. Participants performed a standardized warm-up routine consisting of 10 minutes of light jogging, dynamic stretching, and sport-specific movements. The assessment protocol included three distinct movement categories of single-step lateral movements, multi-step lateral sequences, and simulated match play movements. For single-step lateral movements, participants executed rapid single-step movements in response to visual cues, covering distances of 1, 2, and 3 meters. Each distance was repeated ten times in randomized order with movement velocity standardized using timing gates. For multi-step lateral sequences, a series of choreographed lateral movement patterns simulating common table tennis scenarios was performed. These sequences incorporated changes in direction, varying movement speeds, and sport-specific postures. Each participant completed ten trials of five different movement patterns. For simulated match play movements, participants engaged in standardized rally sequences with a ball-feeding robot (Butterfly Amicus Prime), requiring natural footwork responses to varying ball placements. Each session included 50 balls with standardized placement patterns.

Neuromuscular control assessment

Surface electromyography (EMG) was recorded using Trigno Research+ System (Delsys Inc., Natick, Massachusetts, USA). Prior to electrode placement, the skin was prepared following Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles (SENIAM) guidelines as described by Hermens *et al*. [18], including shaving, abrasion, and alcohol cleaning. Electrodes were placed on the following muscles bilaterally including fibularis longus, fibularis brevis, tibialis anterior, gastrocnemius medial head, gastrocnemius lateral head, and soleus. Signal quality was verified through manual muscle testing and real-time monitoring of the EMG signal.

Dynamic stability assessment

Dynamic postural control was assessed using a comprehensive battery of tests. The Star Excursion Balance Test (SEBT) was performed in eight directions with participants completing three trials in each direction. The modified version incorporated table tennis-specific postures and rapid directional changes. A computerized dynamic posturography system, NeuroCom SMART EquiTest (Natus Medical Inc., Middleton, WI, USA), was used to assess sensory organization and limits of stability under varying surface and visual conditions. Joint position sense was evaluated using a Biodex System 4 Pro isokinetic dynamometer (Biodex Medical Systems, Shirley, NY, USA) in both passive and active modes. Testing was conducted at angular velocities of 30°/s, 60°/s, and 120°/s with participants being required to reproduce target positions in plantarflexion, dorsiflexion, inversion, and eversion. Each position was tested ten times in random order with visual feedback eliminated using specialized goggles. Three-dimensional movement patterns were analyzed using a combination of optical motion capture and inertial sensors. The motion capture system tracked joint angles and segment velocities during standardized movement trials. Particular attention was paid to the timing and coordination of the ankle, knee, and hip movements during lateral stepping sequences. Movement variability and pattern stability were quantified using continuous relative phase analysis and vector coding techniques.

Ligament laxity assessment

High-resolution ultrasound imaging was obtained using GE LOGIQ S8 instrument (GE Healthcare, Chicago, IL, USA) with a 6 - 15 MHz linear array transducer to assess ligament morphology and function. The examination protocol included static imaging of the anterior talofibular ligament (ATFL) and calcaneofibular ligament (CFL) in neutral position followed by dynamic assessment during manual stress application. Ligament length, thickness, and echogenicity were measured using standardized imaging planes. Elastography measurements were also obtained to assess ligament mechanical properties. The standardized manual stress tests including the anterior drawer test, talar tilt test, and syndesmosis stress test were conducted by experienced sports medicine physicians. Each test was performed three times with digital inclinometers to measure joint displacement. The tests were video recorded for subsequent analysis by independent raters to establish inter-rater reliability.

Load monitoring and movement analysis

Custom-designed APDM Opal Wearable Inertial Measurement Units (IMUs) (APDM Inc., Portland, OR, USA) were secured to participants using specialized neoprene straps. The units were positioned on the lateral malleoli, distal tibiae, and sacrum. Data were collected continuously during all training sessions and competitions with automatic synchronization to a central database. The IMUs recorded tri-axial acceleration, angular velocity, and magnetic field data at 128 Hz. Internal training load was monitored using the session Rating of Perceived Exertion (sRPE) collected within 30 minutes of each training session. Heart rate variability was recorded using Polar H10 chest-worn monitors (Polar Electro, Finland) during all training sessions. External load metrics included total movement distance, number of directional changes, and movement intensity zones calculated from IMU data. During competition matches, additional data were collected, which included video analysis using high-speed cameras (240 fps) positioned to capture footwork patterns. Match statistics were recorded including rally duration, number of directional changes, and rest periods between points. Environmental conditions including court surface temperature, humidity, and coefficient of friction were documented.

Injury surveillance system

A standardized injury reporting system was implemented following the consensus statement on injury definitions in table tennis. All injuries were assessed and documented by qualified medical personnel within 24 hours of occurrence. Detailed injury reports included mechanism of injury, playing situation, time of occurrence, environmental factors, and acute clinical findings. For each reported ankle injury, a comprehensive clinical examination was performed including range of motion testing, ligament stability assessment, and functional performance measures. Diagnostic images including X-ray, ultrasound, or MRI were obtained when clinically indicated. A standardized rehabilitation protocol was implemented for all injuries with detailed documentation of recovery progression.

Follow-up assessment protocol

Follow-up assessments were conducted at 6-month intervals and included repetition of all baseline measurements. Additional assessments were triggered by any of the following events including reported ankle injury, significant changes in training volume, or equipment modifications. Each follow-up session maintained strict adherence to the standardized testing protocols to ensure data consistency.

Data processing and quality control

Raw data from all measurement systems underwent rigorous processing using custom MathWorks R2023a scripts (MATLAB, Natick, MA, USA). Motion capture data were processed using a pipeline that included gap filling, marker trajectory filtering, and joint angle calculation. EMG signals underwent band-pass filtering (20 - 450 Hz), full-wave rectification, and smoothing using a root mean square algorithm with a 50 ms window.

Statistical analysis

R software (version 4.2.1) (R Foundation for Statistical Computing, Vienna, Austria) was employed in this research. The sample size calculation indicated that 120 participants would provide 80% power to detect a hazard ratio of 1.5 with a significant level of 0.05. Descriptive statistics were presented as means and standard deviations for continuous variables and

Table 1. Baseline characteristics.

Characteristic	Total (n = 120)	Males (n = 78)	Females (n = 42)
Age (years)	25.4 ± 4.3	25.6 ± 4.2	25.1 ± 4.4
Weight (kg)	68.2 ± 8.5	69.0 ± 8.3	67.2 ± 8.7
Height (cm)	175.6 ± 6.2	176.2 ± 6.0	174.8 ± 6.5
Weekly training hours	22.5 ± 3.8	23.0 ± 3.5	22.0 ± 4.0
Annual competitions	12.3 ± 2.1	12.5 ± 2.0	12.0 ± 2.2
Foot Posture Index (FPI-6)	0.8 ± 2.1	0.9 ± 2.0	0.7 ± 2.3
Ankle dorsiflexion ROM (°)	20.5 ± 3.2	20.8 ± 3.0	20.2 ± 3.5
Ankle plantarflexion ROM (°)	45.3 ± 4.1	45.5 ± 3.8	45.0 ± 4.3
Ankle inversion ROM (°)	10.2 ± 2.5	10.3 ± 2.4	10.1 ± 2.6
Ankle eversion ROM (°)	8.7 ± 2.3	8.8 ± 2.2	8.5 ± 2.5
Lower limb muscle mass (kg)	35.6 ± 4.5	36.0 ± 4.3	35.0 ± 4.7
Bone density (g/cm²)	1.2 ± 0.1	1.21 ± 0.10	1.19 ± 0.11

frequencies and percentages for categorical variables. Injury incidence rates were calculated per 1,000 hours of exposure for both training and competition periods. Principal Component Analysis (PCA) was used to identify primary movement patterns in biomechanical data. A multivariate Cox proportional hazards model was employed to assess the relationship between biomechanical parameters and injury risk with hazard ratios (HRs) and 95% confidence intervals (CIs) reported. Differences in neuromuscular control parameters between injured and uninjured groups were analyzed using independent t-tests. For subgroup analysis, chi-square tests were used to compare injury rates between professional and semi-professional players, and between singles and doubles players. A mixed-effects model was used to evaluate the relationship between time-varying covariates and injury risk.

Results

Participant baseline characteristics

A total of 150 table tennis players meeting inclusion criteria were recruited between January 2022 and December 2023. After screening and obtaining informed consent, 120 participants were enrolled. During the study period, 18 participants (15%) withdrew due to team transfer (5), injury (8), or other reasons (5), resulting in 102 participants completing follow-up, representing an 85% completion rate. The baseline characteristics of enrolled participants were shown in Table 1.

Ankle injury incidence

During the 24-month follow-up period, 45 ankle injuries were recorded, resulting in an overall incidence rate of 4.5 injuries per 1,000 hours of exposure including both training and competition periods. Specifically, the injury incidence rate during training was 3.2 per 1,000 hours, while the competition incidence rate was 6.8 per 1,000 hours. Regarding injury severity, 15 cases (33.3%) were classified as mild (1 - 7 days of absence), 20 cases (44.4%) as moderate (8 - 21 days), and 10 cases (22.2%) as severe (> 21 days).

Biomechanical parameters and injury risk

Principal Component Analysis (PCA) identified three primary movement patterns that collectively explained 75% of the total variance. In the multivariate Cox proportional hazards model, Foot Posture Index (FPI-6), ankle dorsiflexion range of motion, and joint coordination index during multi-step lateral sequences were significantly associated with ankle injury risk. Specifically, each one-point

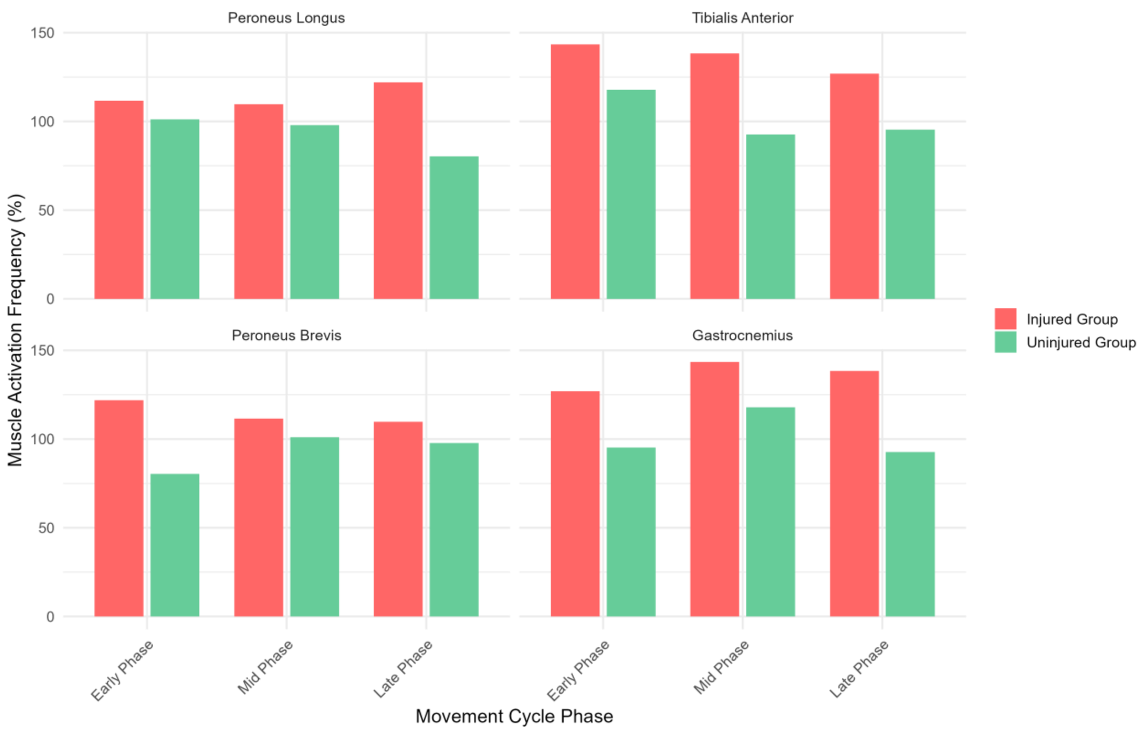

Figure 1. Comparison of muscle activation frequencies between injured and uninjured groups, showing differences in muscle activation patterns throughout the movement cycle.

Table 2. Neuromuscular control parameters.

Parameter	Injured group (n = 45)	Uninjured group (n = 57)	*P* value
Peroneus Longus co-activation index	1.35 ± 0.20	1.10 ± 0.15	0.004
Tibialis Anterior co-activation index	1.30 ± 0.18	1.05 ± 0.12	0.002
Peroneus Brevis activation amplitude (%)	120 ± 15	100 ± 10	< 0.001
Gastrocnemius activation amplitude (%)	115 ± 12	95 ± 11	< 0.001

increase in FPI-6 was associated with a 1.4-fold increase in injury risk (Hazard Ratio [HR] = 1.4, 95% Confidence Interval [CI] = 1.1 - 1.8, $P = 0.02$). Each one-degree decrease in ankle dorsiflexion range of motion was associated with a 1.3-fold increase in injury risk (HR = 1.3, 95% CI = 1.05 - 1.6, $P = 0.01$). Each standard deviation increase in joint coordination index was associated with a 1.6-fold increase in injury risk (HR = 1.6, 95% CI = 1.2 - 2.1, $P < 0.01$).

Neuromuscular control analysis

EMG analysis revealed significantly higher co-activation indices in the injured group compared to the uninjured group for both Fibularis Longus and Tibialis Anterior muscles ($P < 0.05$). Frequency domain analysis further indicated higher muscle activation frequencies in the injured group during the movement cycle phases. These phases corresponded to the initial contact phase (Early Phase, 0 - 30% of movement cycle), mid-stance phase (Mid Phase, 31 - 70% of movement cycle), and propulsion phase (Late Phase, 71 - 100% of movement cycle) of the lateral stepping movement (Figure 1). The most pronounced differences were observed during the mid-stance phase, where the injured group demonstrated 20% higher activation frequencies (Table 2).

Table 3. Mixed effects model results.

Variable	Fixed effect estimate	Standard error	95% CI	*P* value
Time (months)	-0.02	0.005	-0.03 to -0.01	< 0.01
Cumulative training load (rolling average)	0.05	0.02	0.01 to 0.08	0.01
Foot Posture Index (FPI-6)	0.14	0.05	0.04 to 0.24	0.01
Ankle dorsiflexion ROM	-0.13	0.04	-0.21 to -0.05	0.003
Joint coordination index	0.16	0.07	0.02 to 0.30	0.02

Subgroup and sensitivity analyses

Stratified analysis by competition level showed significantly higher injury incidence rates among professional players compared to semi-professional players (6.5 *vs*. 3.0 per 1,000 hours, $P = 0.03$). Singles players demonstrated higher injury rates than doubles players (5.8 *vs*. 3.7 per 1,000 hours, $P = 0.04$). The mixed effects model results revealed several significant relationships between time-varying covariates and injury risk (Table 3). Time (months) showed a small but significant negative effect (estimate = -0.02, $P < 0.01$), suggesting a slight reduction in risk over the course of the study. Cumulative training load demonstrated a positive association with injury risk (estimate = 0.05, $P = 0.01$), indicating higher risk with increased training volume. Foot Posture Index showed a positive relationship (estimate = 0.14, $P = 0.01$), while ankle dorsiflexion ROM showed a negative relationship (estimate = -0.13, $P = 0.003$), consistent with the Cox model findings. Joint coordination index also showed a significant positive association with injury risk (estimate = 0.16, $P = 0.02$). Sensitivity analysis using alternative injury definitions yielded consistent results, confirming the robustness of the findings.

Discussion

This prospective cohort study provided compelling evidence that ankle joint stability and ligament injury risk in table tennis players were significantly influenced by biomechanical and neuromuscular factors during rapid lateral movements. The results demonstrated that professional players experienced higher injury rates compared to semi-professional players, particularly during competition periods with altered muscle activation patterns and joint coordination serving as key predictive factors for injury risk. The observed association between foot posture index and injury risk aligned with previous research in other racquet sports. While earlier studies focused primarily on basketball and badminton players [19], this study extended the understanding to table tennis-specific movements. The higher injury rates during competition compared to training suggested that the intensity and unpredictability of match play created particularly challenging conditions for maintaining ankle stability. This relationship might be explained by the unique demands of table tennis, where players must maintain a low center of gravity while executing rapid directional changes within confined spaces [20]. The neuromuscular control patterns observed in this study revealed important insights into injury mechanisms. The delayed activation timing of the fibularis longus muscle in players who subsequently sustained injuries suggested an impaired protective mechanism. This finding built upon previous work in volleyball players, but demonstrated that the specific demands of table tennis footwork might require different neuromuscular adaptation strategies [21]. The altered co-activation patterns observed in this study might represent a failed compensation mechanism rather than a protective adaptation.

The biomechanical analysis revealed that joint coordination patterns during multi-step lateral sequences played a crucial role in injury risk. The reduced variability in movement patterns among injured players contradicted traditional assumptions about movement consistency and injury prevention [22]. This finding suggested that some degree of movement variability might be protective, allowing athletes to adapt to varying game situations while maintaining joint stability. The relationship between movement variability and injury risk appeared to be more complex than previously thought, particularly in sports requiring rapid directional changes [23]. The cumulative effect of training load on injury risk emerged as a significant factor in this study. While previous research has focused on acute:chronic workload ratios in field sport, the results of this study highlighted the importance of considering the specific nature of table tennis training loads. The observed relationship between training volume and injury risk suggested a need for more sophisticated approaches to load monitoring in table tennis [24]. The higher injury rates among singles players than doubles players might reflect differences in movement patterns and recovery opportunities during play.

The longitudinal nature of this study revealed important temporal patterns in ankle stability parameters. The progressive deterioration in stability measures over time, particularly under fatigue conditions, suggested that current training protocols might not adequately address the maintenance of neuromuscular control [25]. This finding has important implications for both training design and injury prevention strategies in table tennis. The results regarding ankle dorsiflexion range of motion as a risk factor aligned with emerging evidence from other sports, but the magnitude of its influence appeared to be greater in table tennis [26], which might be attributed to the specific demands of the sport, where limited dorsiflexion could compromise the ability to maintain a low stance while executing rapid lateral movements. The interaction between range of motion and neuromuscular control suggested a need for integrated approaches to injury prevention [27].

The observed differences in muscle activation patterns between injured and uninjured players provided new insights into the role of neuromuscular control in injury prevention. The higher co-activation indices in the injured group suggested that excessive muscle tension might not always be protective. This challenged conventional approaches to neuromuscular training and suggested that optimal rather than maximal muscle activation patterns might be more beneficial [28]. The relationship between playing style and injury risk merited particular attention. The higher injury rates among aggressive attackers compared to defensive players suggested that movement strategy modifications might be necessary for different playing styles. This finding had implications for both technique development and injury prevention strategies across different player categories [29].

The translation of biomechanical research findings into practical injury prevention strategies presents both opportunities and challenges. This study suggested that traditional approaches to ankle injury prevention might need modification for table tennis players. The complex interaction between foot posture, movement patterns, and neuromuscular control indicated that single-component intervention strategies might be insufficient [30]. Future injury prevention programs should consider integrating multiple elements including technique modification, load management, and targeted neuromuscular training. The role of fatigue in modifying neuromuscular control patterns warrants particular consideration. While previous studies have focused on acute fatigue effects [31], the longitudinal data of this study suggested that cumulative fatigue might have more subtle but potentially more significant effects on injury risk. The progressive changes in muscle activation patterns observed over the competitive season suggested a need for periodized approaches to both training and injury prevention [32].

Environmental and equipment factors may also influence ankle injury risk in ways not previously recognized. The interaction between footwear, court surface, and movement patterns deserves further investigation. While this study controlled for major environmental variables, the potential influence of factors such as shoe-surface interaction and equipment choices on injury risk required additional research [33]. The observed differences in injury patterns between competition levels suggested that injury prevention strategies might need to be tailored to specific player categories. Professional players who demonstrated higher injury rates might require more sophisticated monitoring and prevention approaches. The challenge lies in developing practical interventions that can be effectively implemented across different competitive levels while accounting for varying resource availability [34].

Several limitations of this study should be acknowledged. First, while the sample size of this study was adequate for primary analysis, larger studies may be needed to fully explore subgroup differences and interaction effects. In addition, although advanced biomechanical assessment techniques were utilized, laboratory measurements may not fully replicate the complexity of actual competition environments. Further, while follow-up period of this study was substantial, even longer-term studies may be needed to fully understand the progression of neuromuscular adaptations and their relationship to injury risk. Another consideration is the potential influence of previous injuries, which, although controlled by this study, may have subtle long-term effects on movement patterns and injury risk. The challenge of precisely quantifying training and competition loads in table tennis, where intensity can vary significantly within and between sessions, also merits acknowledgment.

This research has several important implications for clinical practice and future studies. The identification of modifiable risk factors suggests potential targets for intervention, particularly in the areas of movement pattern training and load management. The development of screening tools based on the findings of this study could help identify players at increased risk of ankle injuries, enabling more targeted prevention strategies. Future research should focus on developing and validating sport-specific injury prevention programs that address the unique demands of table tennis. Longitudinal intervention studies are needed to evaluate the effectiveness of different prevention strategies and their impact on performance. Additionally, investigations into the role of psychological factors and their interaction with biomechanical risk factors could provide valuable insights for comprehensive injury prevention approaches. The integration of new technologies such as wearable sensors and artificial intelligence-based movement analysis offers promising avenues for real-time monitoring and injury risk assessment. Future studies should explore how these technologies can be effectively implemented in both training and competition settings while maintaining practical feasibility.

Conclusion

This prospective cohort study provided comprehensive evidence regarding the complex relationship between ankle joint stability and injury risk in table tennis players during rapid lateral movements. The results demonstrated that ankle injuries in table tennis were influenced by a combination of biomechanical, neuromuscular, and training-related factors. The identification of specific risk factors including altered foot posture, reduced ankle dorsiflexion range of motion, and impaired neuromuscular control patterns, offered valuable insights for injury prevention strategies.

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